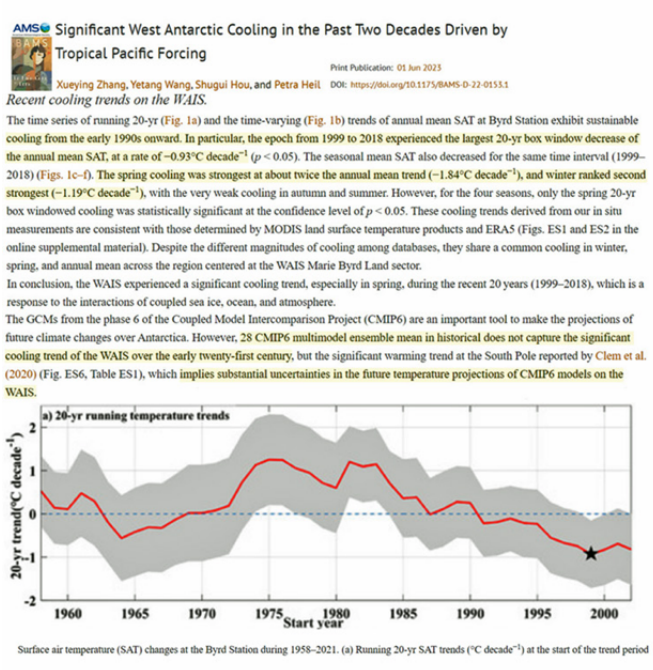
Antarctica Is Colder, Icier Now Than Any Time In 5000 Years. The Last Warm Period Was 1000 Years Ago.

By Kenneth Richard on 15. April 2024

More evidence emerges that Antarctica has undergone rapid glacier and sea ice expansion in recent centuries, in line with the long-term and recent Antarctic cooling trend.

West Antarctica's mean annual surface temperatures cooled by more than -1.8°C (-0.93°C per decade) from 1999-2018 (Zhang et al., 2023).

Not just West Antarctica, but most of the continent also has cooled by more than 1°C in the 21st century. See, for example, the ~1°C per decade cooling trend for East Antarctica (2000 to 2018) shown in Fig. ES1 (right).



AMS Significant West Antarctic Cooling in the Past Two Decades Driven by Tropical Pacific Forcing

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Recent cooling trends on the WAIS.

The time series of running 20-yr (Fig. 1a) and the time-varying (Fig. 1b) trends of annual mean SAT at Byrd Station exhibit sustainable cooling from the early 1990s onward. In particular, the epoch from 1999 to 2018 experienced the largest 20-yr box window decrease of the annual mean SAT, at a rate of −0.93°C decade^{-1} ($p < 0.05$). The seasonal mean SAT also decreased for the same time interval (1999–2018) (Figs. 1c–f). The spring cooling was strongest at about twice the annual mean trend (−1.84°C decade^{-1}), and winter ranked second strongest (−1.19°C decade^{-1}), with the very weak cooling in autumn and summer. However, for the four seasons, only the spring 20-yr box windowed cooling was statistically significant at the confidence level of $p < 0.05$. These cooling trends derived from our in situ measurements are consistent with those determined by MODIS land surface temperature products and ERA5 (Figs. ES1 and ES2 in the online supplemental material). Despite the different magnitudes of cooling among databases, they share a common cooling in winter, spring, and annual mean across the region centered at the WAIS Marie Byrd Land sector.

In conclusion, the WAIS experienced a significant cooling trend, especially in spring, during the recent 20 years (1999–2018), which is a response to the interactions of coupled sea ice, ocean, and atmosphere.

The GCMs from the phase 6 of the Coupled Model Intercomparison Project (CMIP6) are an important tool to make the projections of future climate changes over Antarctica. However, 28 CMIP6 multimodel ensemble mean in historical does not capture the significant cooling trend of the WAIS over the early twenty-first century, but the significant warming trend at the South Pole reported by Clem et al. (2020) (Fig. ES6, Table ES1), which implies substantial uncertainties in the future temperature projections of CMIP6 models on the WAIS.

Surface air temperature (SAT) changes at the Byrd Station during 1958–2021. (a) Running 20-yr SAT trends (°C decade^{-1}) at the start of the trend period

Fig. ES1 Spatial distribution of trends in annual and seasonal mean MODIS land surface temperature from 2000 to 2018, modified from Retamales-Muñoz et al. (Retamales-Muñoz et al. 2019).

Image Source: Zhang et al., 2023

According to a new study, about 6000 years ago Antarctica's Collins

Glacier's frontline was a full 1 km southwest of its current extent. The frontline advanced to today's extent ~5000 years ago.

"Previous studies proposed that 6000 yr BP, the frontline position of the Collins Glacier was located 1 km further south west than the present, and that the current frontline was first attained at approximately 5000 yr BP."

The glacier then continuously retreated south of the modern extent for another 4000 years, with peak ice loss 1000 years ago (as shown in the 1000-year "Proglacial lake environment" image). In the last 1000 years this glacier has rapidly re-advanced back to the glaciated extent from 5000 years ago, which is in line with the sustained cooling trend ongoing since the Medieval Warm Period.

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Prokaryotic richness and diversity increased during Holocene glacier retreat and onset of an Antarctic Lake

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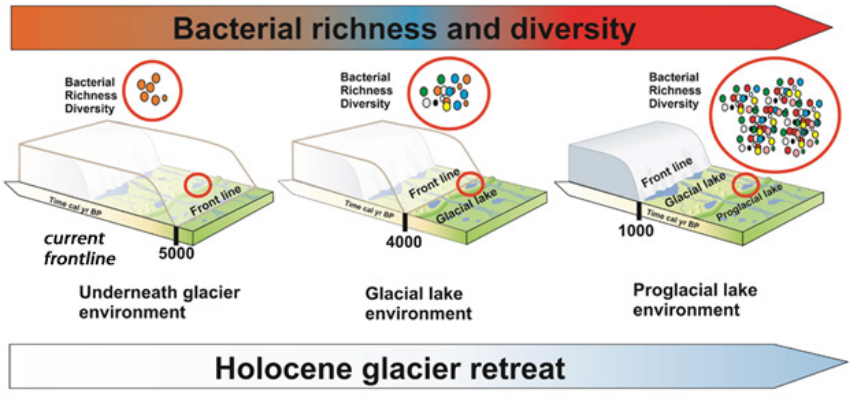
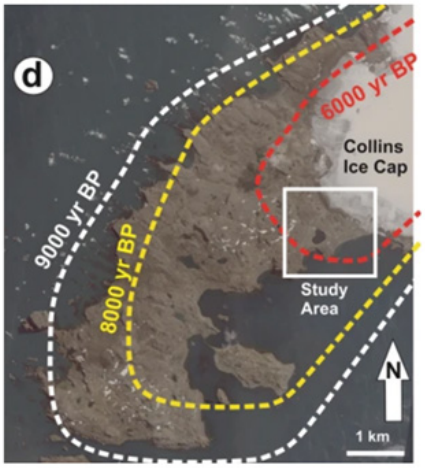
Previous studies proposed that 6000 yr BP, the frontline position of the Collins Glacier was located 1 km further south west than the present, and that the current frontline was first attained at approximately 5000 yr BP[13] (Fig. 1d, e). Although based on different kind of data (spatial vs. a single habitat chronosequence), the lowest ASV richness and diversity found in this glacier-covered phase (4910–3853 cal yr BP) seems to be in line with the findings of Cauvy-Fraunié and Dangles (2019), who studied global biodiversity and demonstrated that taxon abundance and richness generally increase at lower levels of glacier influence. The authors propose that glacier retreat would increase local biodiversity in the newly formed lakes and that the observed increased richness is mostly explained by the rise in generalist taxa, whereas specialist, ice-dwellers organisms are lost[3].

The Holocene process of deglaciation within the Fildes Peninsula (Fig. 1d) has been inferred by Mäusbacher et al. (1989) and confirmed by Oliva et al. (2023). They proposed three main stages of the Collins Ice Cap frontline position. By 9000 yr BP, the frontline position was located on the surrounding southwestern most tip of the peninsula[13,15]. Towards 8000 yr BP, the frontline had migrated about 1 km towards the center of the peninsula and by 6000 yr BP, the frontline position had shifted to about 500 m away from the position of Lake Profound. This process of frontline migration was explained due to a combination of both climate warming and sea level rise control[14,45]. In this regard, Hall (2007) also inferred that by 3500 yr BP the frontline position had migrated to 400 to 500 m southwest away from the contemporary frontline position. This means that Lake Profound's formation can be assigned to the middle Holocene[12].

Finally, the C/N ratio stabilization together in the upper zone (2653 – 1074 cal yr BP) with the visual moss content and the distinct series of silt-lamination clearly shows the initial stages of stable lake conditions and the loss of an active connection with the glacier frontline. The highest and most stable TOC and TN values observed here indicate a most intense biological colonization within the lake until ca. 1000 cal yr BP. Accordingly, this zone showed the highest values of prokaryotic richness and diversity. Shannon diversity values were similar to those Different aspects of Holocene proglacial lake formation around the frontline of Collins Glacier were already addressed by refs. [12,13,14] and [15]. The reconstruction of the glacier frontline migration in these studies (Fig. 1d) indicates that Lake Profound's formation can be assigned to the middle Holocene. Based on the increase in TOC concentration and abundance/composition of diatom valves, Schmidt et al. (1990) inferred the onset of genuine limnological conditions after 3155 yr BP and attributed this process to increased glacier erosion and sediment influx due to warming temperatures[17].



Left: glacier environment exhibiting the lowest bacterial diversity and richness at ~5000 cal yr BP. Center: transition to a glacial lake environment that was associated with an increase in bacterial richness and diversity. Right: the highest bacterial diversity and richness found after the onset of a proglacial lake fully separated from the Collins Glacier. The chronology of glacier retreat is in accordance with Fig. 1 as inferred from Ref. [13].



d Holocene migration of Collins Glacier frontline position at 9000, 8000 and 6000 yr BP[13]

Image Source: Piccini et al., 2024

Throughout the Holocene (Medieval Warm Period, Roman Warm Period, and earlier) and until a few hundred years ago (from ~7100 to 500 years before present), coastal Antarctica's Victoria Land (VLC) was substantially warmer than today. The Ross Sea was also sufficiently ice-free to allow for elephant seal populations (as large as ~200,000 individuals) to thrive at 73-78°S.

Today, however, elephant seal populations – which require extended sea ice-free sea waters to breed, forage, and provide nourishment for their pups – can no longer subsist anywhere even remotely close to the coasts of the Antarctic continent. It is now too cold and the sea ice is too extensive.

The substantially reduced number of remaining elephant seals existing today can only survive on subantarctic islands (South Georgia, Macquarie) at southern South American latitudes (~54.5°S) situated 2400 kilometers north of VLC (Koch et al., 2019).

The "genetically distinct" VLC elephant seal populations that endured throughout the Holocene and even through Medieval times have tragically died off in the last few centuries due to the modern-era cooling gradient and subsequent ice cover expansion (Hall et al., 2023).

"Across all sites, there is a precipitous drop in the number and geographic extent of the SES [southern elephant seals] remains within the last millennium"

"...the documented population crash and abandonment of the entire coast by SES after ~1000-500 yr BP was due to return of heavy sea ice"

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Widespread southern elephant seal occupation of the Victoria land coast implies a warmer-than-present Ross Sea in the mid-to-late Holocene

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In 2006, we suggested a pre-historic presence of SES on the Ross Sea VLC (Hall et al., 2006). Based on our initial, but limited dataset, we proposed that these seals may have been present during the Holocene and that extensive sea ice led to their exclusion from the present-day coast. Here, we present a more comprehensive dataset of radiocarbon-dated molted skin/hair, mummified and skeletal remains, and whiskers covering ~7000 yrs and at least 73-78° S latitude. These data show the widespread presence of SES along the VLC, which we attribute to the reduction or absence of landfast ice, as well as warmer ocean temperatures over much of the Holocene compared to today.

The presence of abundant SES remains on the VLC is unexpected. Today, this species is based largely on subantarctic islands, such as South Georgia, Kerguelen, and Macquarie (Fig. 2). A few hundred sub-adult males from subantarctic colonies molt on the East Antarctic coast near Vincennes and Prydz Bays polynyas (~66° S; Gales and Burton, 1989; van den Hoff et al., 2003).

Of 101 tracked animals, just one penetrated onto the extensive Ross Sea continental shelf, though well offshore from Victoria Land. In addition, pack-ice expansion (both in duration and extent) in the Ross Sea over the last several decades (Comiso et al., 2011; Stammerjohn et al., 2008, 2012; Turner et al., 2015, 2016) has been linked to reduced female foraging in this region, consequent low weaning weights and survival of pups, and ultimately the decline of the Macquarie Island population (McMahon et al., 2000; van den Hoff et al., 2014; Hindell et al., 2016, 2017; Clausius et al., 2017; Volzke et al., 2021). Thus, sea ice has a large effect on SES populations not only by limiting their ability to access haul-out sites (through the presence/absence of summer landfast ice), but also through impacts on foraging success (because of pack-ice density, particularly for juveniles and females; e.g., Bester, 1988).

Satellite imagery shows the density of end-of-summer landfast ice along the coast is substantial, despite open water and pack ice tens of kilometers to the east (Fig. 1). Because of the propensity of SES to favor open coasts, we attribute the lack of these seals today to the development of summer landfast ice in the late Holocene.

Across all sites, there is a precipitous drop in the number and geographic extent of SES remains within the last millennium, with only few samples dating to <600 yr BP and none to <~400 yr BP.

The general pattern of seal distribution is in accord with aDNA analysis of SES remains from this region. De Bruyn et al. (2009, 2014) found that VLC seals represented a distinct breeding population (breeding either along the VLC or at unsampled sites farther north), genetically distinct from any modern SES. This Victoria Land population may have been founded by seals that migrated from Macquarie Island during deglaciation and established a permanent occupation that rapidly increased in diversity (de Bruyn et al., 2014).

VLC population expanded rapidly until about 1000 yr BP, when it underwent a significant, irreversible population crash and loss of diversity. Effective population size prior to the collapse was approximately 200,000 individuals, much greater than the reconstructed size of the coeval Macquarie population (de Bruyn et al., 2014).

We infer that the documented population crash and abandonment of the entire coast by SES after ~1000-500 yr BP was due to return of heavy sea ice (particularly summer landfast ice), the greatest of the postglacial period, and likely cold ocean temperatures. We speculate that these conditions also may have resulted in contraction of the Cape Adare Adélie penguin "super colony" (Emslie et al., 2018), as well as the disappearance of this species at Cape Irizar (Emslie, 2021).

The interpretation of the SES record is consistent with geomorphic evidence from raised beaches that indicates 1) a long period in the Holocene of ice-free conditions at the immediate shoreline based on landforms and sediments indicative of open water; and 2) expansion of VLC glaciers in the last millennium following a long period of restricted glacier extent (e.g., Baroni and Orombelli, 1994b; Hall and Denton, 2002). For example, the Wilson Piedmont Glacier, as well as the Nansen and Hell's Gate ice shelves, have advanced over Holocene raised beaches within the last few centuries (Stuiver et al., 1981; Hall and Denton, 2002; Baroni and Hall, 2004).

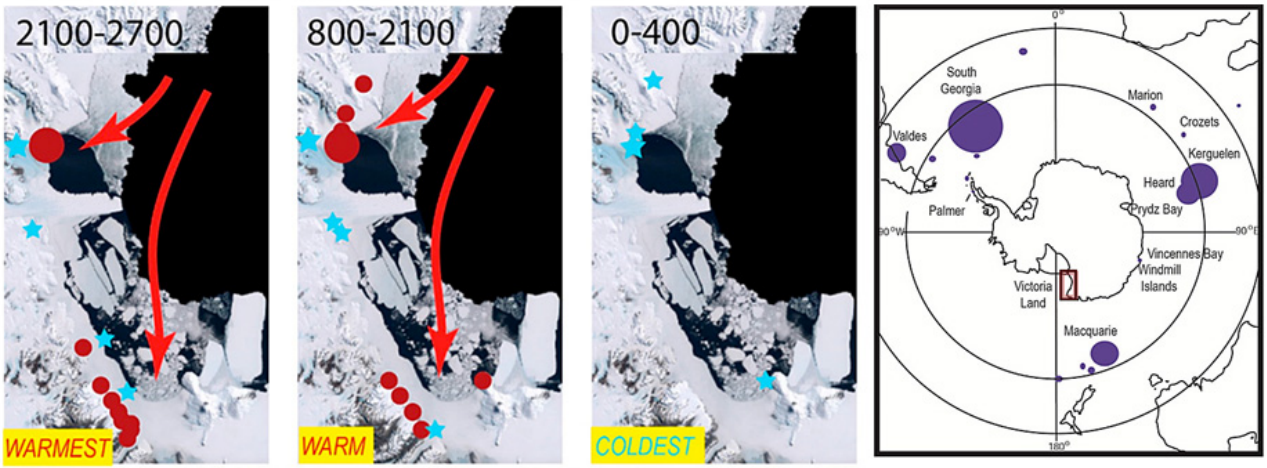

Fig. 8. Schematic of different time periods along the Victoria Land coast showing inferred relative ocean water temperature/sea ice. Red dots = elephant seals; blue stars = Adélie penguins (Baroni and Orombelli, 1994a; Dochat et al., 2000; Hall et al., 2004; Hu et al., 2013; Emslie, 2021; Gao et al., 2022). Red arrows indicate possible intrusion of modified circumpolar deepwater (dashed = weak). Times at top of panels are in years BP. Base image is from the Landsat Mosaic Image of Antarctica (https://lima.usgs.gov).

Fig. 2. Location of primary southern elephant seal colonies, with circles denoting relative size (after LeBoeuf and Laws, 1994). The black box marks the Victoria Land coast.

Image Source: Hall et al., 2023

And with the modern sea surface temperatures cooling and southern

hemisphere sea ice expansion in recent decades, even the subantarctic islands in the South Pacific that SES are limited to occupying today may not be sufficiently warm and ice-free to accommodate remaining populations. Today's southern elephant seals are thus ironically threatened by *cooling* in the era of anthropogenic global warming.

"[P]ack-ice expansion (both duration and extent) in the Ross Sea over the last several decades has been linked to reduced female foraging in this region, consequent low weaning weights and survival of pups, and ultimately the decline of the Macquarie Island population."

Interestingly, Hall et al. also report that not only have the last few centuries (including the present) been "the coldest, iciest conditions in the post-glacial period" (see the blue sea ice and red temperature trend lines on the Holocene timeline), but even *the last glacial period* had periods (~50,000 to 25,000 years ago) with less sea ice than today, allowing SES to occupy the VLC coast.

Image Source: Hall et al., 2023